VARIATION OF LONGITUDINAL BEAM POSITION AND PROFILE DURING ACCELERATION IN TRISTAN MAIN RING

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Abstract

Behavior of a highly bunched beam has been observed during acceleration in TRISTAN Main Ring (MR) using a streak camera. The longitudinal beam profile and bunch position can be calculated by potential well distortion theory, provided with an appropriate wake potential in the storage ring. The longitudinal wake potential was derived from the measurement of higher order mode loss in TRISTAN MR. The calculation of the current distribution explains observations of bunch behavior.

Introduction

A wake field generated from the interaction of a highly bunched beam with resonant structures in the storage ring produces not only energy loss and overheating of vacuum components but instabilities of beam. The heavily collective effects are conceived to limit performance of a large storage ring, such as TRISTAN and LEP operating in a short bunch and high peak current.

The TRISTAN MR has been operated with 104 RF cavities at the maximum energy of 28 GeV. A single bunch current seems to be limited to around 5 mA at the tuned operation. This limitation appears to be caused immediately by synchro-beta resonances. A stability of beam has been strictly influenced by RF voltage. An unstable region of bunch current occurred depending on RF voltages. At a certain RF voltage the coupled bunch instability has limited the bunch current. The vacuum pressure has risen up locally at vacuum chambers as the current increased. These phenomena result from the collective wake field generated in RF cavities and vacuum components with high coupling impedances. It is of importance to investigate a wake potential of the storage ring in order to understand collective effects and to cure them.

In this work the higher order mode loss in TRISTAN MR was measured for various bunch lengths using the streak camera. From these data the longitudinal wake potential was evaluated in terms of discrete resonant modes of RF cavity and an analytic extension for higher modes. The longitudinal beam profile observed during acceleration was compared with a current distribution computed by the potential well distortion theory.

Measurement of Longitudinal Beam Profile

The measurement is based on observation of a longitudinal profile of the synchrotron light emitted from a bunched electron beam. The synchrotron light radiated at the bending arc of the ring is brought out through the optical system[1] and focused on the streak camera, Hamamatsu C1587 with M1955 synchro-scan unit and M2887 dual time base unit. The shutter of the camera is triggered by a clock synchronized with the revolution. Once triggered, photoelectrons in the camera are vertically deflected in a sine wave whose frequency is 1/4 of RF frequency. Besides the usual pair of vertical deflectors, it has another pair which scans the streak image horizontally. We can thus observe the streak image of each revolution, or the image of each bunch of each revolution with time resolution of 6 ps.

A streak picture is digitized into 256 by 256 elements. The intensity of each element is digitized into 8 bits. Each picture contains 10 traces. The data of each trace for a single bunch is horizontally integrated to give one dimensional longitudinal distribution y_i. Following quantities are then calculated:

$$\begin{aligned} \bar{t} &= (1/n)\sum y_i t_i, \\ \sigma^2 = m_2 &= (1/n)\sum y_i (t_i-\bar{t})^2, \\ m_3 &= (1/n)\sum y_i (t_i-\bar{t})^3, \\ s &= m_3/m_2^{3/2}, \end{aligned} \quad (1)$$

where $n=\sum y_i$. The quantity $\bar{t}$ characterizes the bunch position. The quantity σ is the rms bunch length. The last quantity s is called skewness in statistics, which we use here as a measure of distortion of the Gaussian distribution. It has no dimension, and is zero when the distribution is perfectly symmetric. Statistical errors of the experimental data are calculated from traces on a single streak picture.

Higher Order Mode Loss and Wake Potential

The higher order mode loss was derived from measuring the shift in equilibrium bunch position as a function of current for various bunch lengths using streak pictures. A pedestal bunch with a low current was filled in the bucket preceding a main bunch with a high current by a half revolution. Since the wake field of the pedestal bunch does not affect the main bunch, a time shift in the position of two bunches is related to the loss parameter k.

$$k = -\frac{V_c}{\Delta I T_0}\left[\frac{1-\cos(\omega_{RF}\Delta t)}{q} + \sqrt{1-\left(\frac{1}{q}\right)^2}\sin(\omega_{RF}\Delta t)\right], \quad (2)$$

where V_c is the peak RF voltage, T_0 the revolution time, $\omega_{RF} = 2\pi f_{RF}$, f_{RF} the RF frequency, $q=V_c/U_0$, U_0 the synchrotron radiation loss per turn, ΔI the current difference between two bunches and Δt the time shift between two bunch positions. The time shift between two bunches and the bunch length was measured for several bunch currents at 7.5 GeV varying RF voltage. The data for $V_c = 22.6$ MV are plotted in Fig. 1. The loss parameters obtained from eq. (2) are plotted as a function of the bunch length in Fig. 2.

The loss parameter is calculated from the longitudinal wake potential $w(\tau)$ for a Gaussian bunch with the bunch length σ

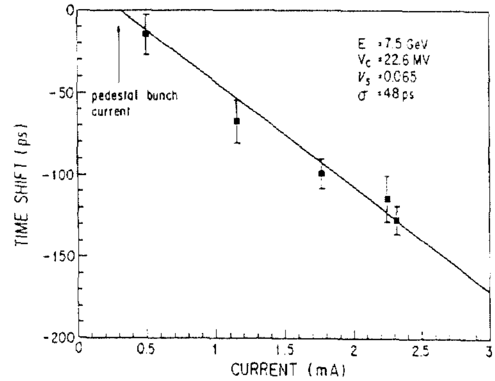

Fig. 1 The time shift between the pedestal and main bunches measured for V_c = 22.6MV at 7.5 GeV.

$$k(\sigma) = \frac{1}{2\sqrt{\pi}\sigma} \int_0^\infty w(\tau) \exp(-\frac{\tau^2}{4\sigma^2}) d\tau. \quad (3)$$

The longitudinal wake potential can be expressed by[2]

$$\begin{aligned} w(\tau) &= \frac{1}{2} \sum_{n=1}^{\hat{n}} \omega_n \left(\frac{R}{Q}\right)_n \cos(\omega_n \tau) \\ &+ C_{sv}\omega_{sv} \Big[\frac{\pi}{4}(1+4x)e^{2x}\mathrm{erfc}(\sqrt{2x}) - \sqrt{\frac{\pi x}{2}} \\ &- 2\int_0^s \frac{u(u+1)\cos xu^2}{(u^2+2u+2)^2} du\Big], \end{aligned} \quad (4)$$

where $x = \omega_{sv}\tau$ and $s = \sqrt{\hat{\omega}/\omega_{sv}}$. The first term gives the wake potential which is obtained from discrete resonant modes of a RF cavity truncating infinite series at a number $\hat{n}$. The resonant frequencies ω_n and ratios $(R/Q)_n$ of shunt impedance to quality factor have been found with the computer program URMEL[3] for $\hat{n}$ = 99 higher order modes of 9 cell APS cavity up to $\hat{\omega}/2\pi$ = 2.1 GHz. The dashed line in Fig. 2 shows $k(\sigma)$ obtained from only a sum of 99 modes over 104 RF cavities. Clearly the loss parameter calculated from only the first term gives too small magnitude for short bunches. The second term is an analytic extension for the missing part of the infinite sum. This missing part is estimated with the optical resonator model. The quantities C_{sv} and ω_{sv}, which are called the "Sessler-Vainshtein" constant and frequency, respectively, should be evaluated so as to fit the experimental data of the loss parameter. We found C_{sv} = 965 kΩ and ω_{sv} = 13.2 GHz. The solid line in Fig. 2 shows the total loss parameters calculated from eq. (3) with the wake potential expressed in terms of a finite sum of resonant modes and an analytic extension for the missing modes. The longitudinal wake potential evaluated is shown in Fig. 3(a).

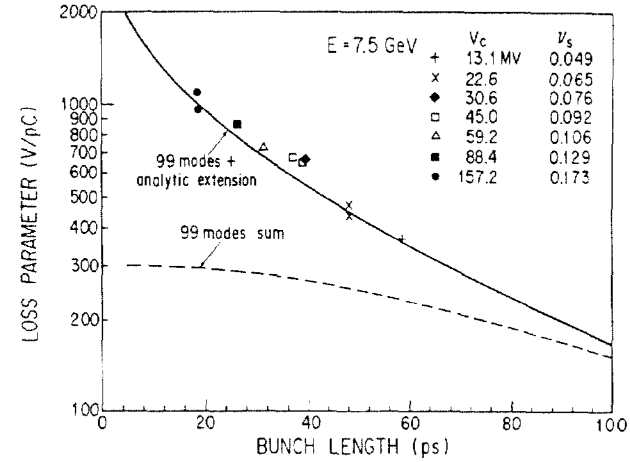

Fig. 2 The loss parameter as a function of the bunch length. The dashed line shows the sum of the lowest 99 modes of RF cavities. The solid line is a fit to data in terms of 99 cavity modes and the analytic extension for higher modes.

Current Distribution due to Potential Well Distortion

The distribution of charged particles in the storage ring is influenced by the wake field. As modified by potential well distortion, the equilibrium longitudinal distribution of electrons satisfies[4]

$$I_n(t) = K \exp\Big(-\frac{t^2}{2\sigma^2} - \frac{G}{\sigma^3}\int_0^\infty s(\tau) I_n(t-\tau) d\tau\Big), \quad (5)$$

where $I_n(t) = I(t)/I_p$ and I_p is the peak current of the unperturbed Gaussian bunch. The constant K is chosen so as to satisfy $\int_{-\infty}^{+\infty} I_n(t)dt = \sqrt{2\pi}\sigma$, where σ is the unperturbed bunch length. The parameter $G = \alpha I T_0^2/(2\pi)^{5/2}\nu_s^2 E$ is a measure of the strength of the potential well distortion, where α is the momentum compaction factor, ν_s the synchrotron tune and E the beam energy. The $s(\tau)$ shown in Fig. 3(b) is the step response wake function given by the integral of the impulse wake potential $w(\tau)$. The current distribution $I(t)$ is obtained by the self-consistent solution of eq. (5) which can be solved numerically for given $s(\tau)$, G and σ assuming the unperturbed Gaussian distribution.

From resultant current distributions, the center of charge, the rms bunch length and the skewness of bunch shape are calculated by the definition of eq. (1). In particular the time shift in the center of charge is related to the loss parameter $k = -\bar{t}/\sqrt{2\pi}G$.

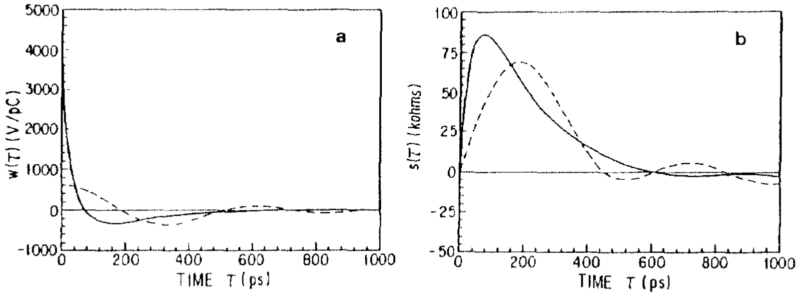

Fig. 3 (a) The impulse wake potential as a function of time. (b) The step response wake function used in the calculation of potential well distortion. The dashed line is the sum of 99 cavity modes. The solid line shows the wake function superimposed with the analytic extension.

Longitudinal Beam Profile During Acceleration

The longitudinal beam profile was observed with the streak camera during acceleration from 7.5 GeV injection energy to 28 GeV flat top energy. In the normal TRISTAN operation the wiggler magnets have been excited at the injection in order to stabilize beams. The field of wiggler magnets has been operated with a somewhat complex pattern. The RF voltage has been also operated with a pattern as a function of the beam energy, to avoid the beam instabilities at the injection and to keep a sufficient beam lifetime at the flat top. The RF frequency has been slightly changed around the nominal frequency f_{RF} = 508.5808 MHz in order to control the damping partition number. Since these parameters influence on the bunch profile, they are shown as a function of the beam energy in Fig. 4.

From the streak pictures taken in the normal operation, the relative bunch position, the bunch length and the skewness are derived as plotted in Fig. 6 (a)~(c). In these figures the dashed line shows the synchronous position relative to the crest of RF voltage and the bunch length predicted from operational parameters.

The current distribution of a 3 mA bunch was computed from eq. (5) at each energy during acceleration as shown in Fig. 5. We can see that large distortion of the bunch shape at the injection energy is approaching to a Gaussian distribution as the energy rises. In Fig. 5 the maximum peak current occurres at the shortest bunch around 20 GeV at which the loss parameter reaches 940 V/pC. The bunch synchronous position, the bunch length and the skewness derived from the computed current distribution are shown with the solid line in Fig. 6 to compare with the experimental data. The calculation

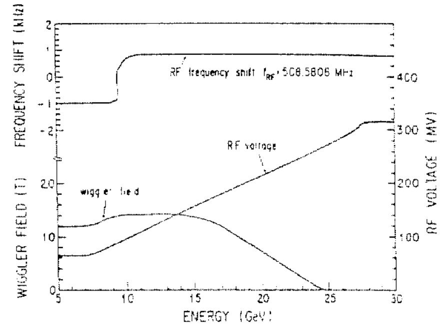

Fig. 4 The wiggler field, the RF cavity voltage and the RF frequency shift in TRISTAN MR operation as a function of the beam energy.

describes the bunch lengthening at the lower energies than 15 GeV and the shortening at higher energies than 20 GeV. The observations of the shift of bunch position and the skewness are explained qualitatively by the potential well distortion but somewhat smaller than the calculation.

Conclusion

The higher order mode loss in TRISTAN MR was obtained from measurement of the time shift in the bunch position using the streak camera. The longitudinal wake potential was found in terms of the finite sum of resonant modes of RF cavity and the analytic extension for higher modes so as to fit the measured loss parameters. The potential well distortion theory explains the longitudinal beam profile observed with the streak camera during acceleration assuming the wake potential evaluated in this work.

References

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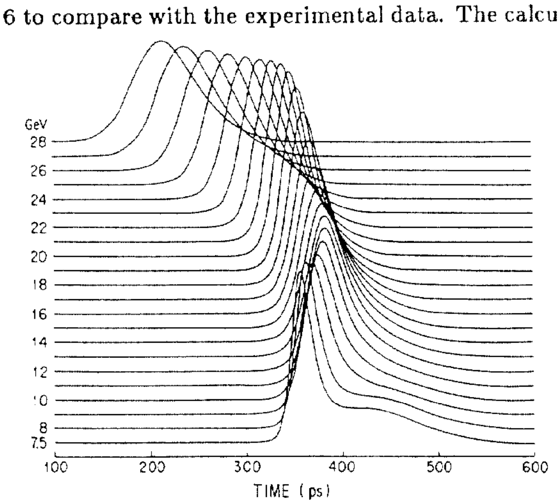

Fig. 5 The current distributions computed for a 3 mA bunch at various beam energies during acceleration. The energy ranges from 7.5 GeV to 28 GeV in 1 GeV step.

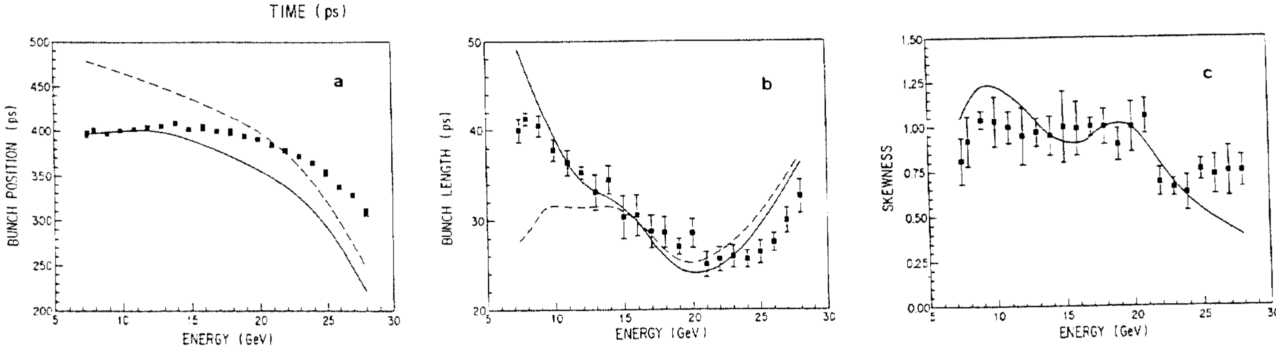

Fig. 6 (a) The bunch position, (b) the bunch length and (c) the skewness as a function of beam energy.